THE MUTUAL INTERPRETATION OF ACTIVE AND PASSIVE MICROWAVE SENSOR OUTPUTS

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ABSTRACT

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The interpretation of surface characteristics from microwave sensor outputs alone is more effective when data is available from both active (radar) and passive (radiometer) sensors. This is because both outputs are determined by the complete scattering pattern of the surface; of which one aspect (backscatter) is estimated by the radar and another (albedo) is estimated by the radiometer. However, because the radiometer output is the convolution of the desired radiation temperature of the surface and the antenna pattern, it is first suggested that this instrumental bias be removed (a simple "bootstrap" method is outlined).

An example is given, used to show that the correction is a significant one for current radiometer performance, and should be applied by those investigators wishing to make quantitative interpretations of apparent surface temperatures.

As examples of the interdependence of active and passive sensor outputs, and their relation to significant surface properties, results are given for two series of measurements, made almost simultaneously with radar and radiometer sensors (at 10 GHz and 35 GHz) over well controlled terrain (vegetation - Purdue Agronomy Farm, Indiana; pumice - Mono Crater, California). In each case the data from one sensor is used to give a more detailed explanation of the output of the other, and the combined sensor outputs interpreted in terms of measurable surface characteristics (roughness scale, dielectric-constant, density, water content).

Author

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THE MUTUAL INTERPRETATION OF ACTIVE AND PASSIVE MICROWAVE SENSOR OUTPUTS

I. INTRODUCTION

Although the investigation of the surface properties of the earth by active and passive microwave sensors is as yet in its infancy, it is not too early to consider some of the advantages of using the outputs of both types of sensors, at a common frequency, in the interpretation process. We are not concerned here with schemes for identifying a particular class of target by comparing a number of sensor outputs ("target signatures") against a stored library, where an extra sensor merely adds one dimension to some multidimensional "sensor space". Rather we are interested in exploiting the relation between the back-scattering coefficient and the albedo of certain classes of surface, with the hope of obtaining information which might not be accessible from radar or (microwave) radiometer data alone. The most obvious example of this combined interpretation is the estimation of actual surface temperature from a radiometer temperature, using an emissivity inferred from the character and magnitude of the radar return. Other examples, together with some supporting measurements, are given in part 3. Before discussing them, it may be desirable to review briefly the significant parameters for the surface, and for the sensors.

II. RELATION BETWEEN SURFACE PARAMETERS AND SENSOR OUTPUT

For the class of surface of interest here (natural surfaces either bare or vegetation covered), the controlling parameter at microwave frequencies is the bistatic scattering cross-section per unit area, $\sigma_{jk}(i, s)$; here (see Fig. 1a), the first subscript (j) refers to the polarization state of the radiation incident on the surface area A, the second subscript (k) designates a particular polarization component of the scattered radiation, and the variables i, s refer to the angles defining the propagation direction (θ_i, ϕ_i) and (θ_s, ϕ_s) of the incident and scattered radiation. If an area A (Fig. 1) is illuminated by a plane wave of power density I_o watts/meter^2 (in polarization state j), and this produces an intensity I_s watts/meter^2 (in polarization state k) at distance R, the cross-section $\sigma_{jk}(i, s)$ is defined through

$$(1) \qquad \sigma_{jk}(i, s) \equiv 4\pi R^2 I_s/(AI_o) = \sigma_{kj}(s, i) \quad \text{(reciprocity theorem)}.$$

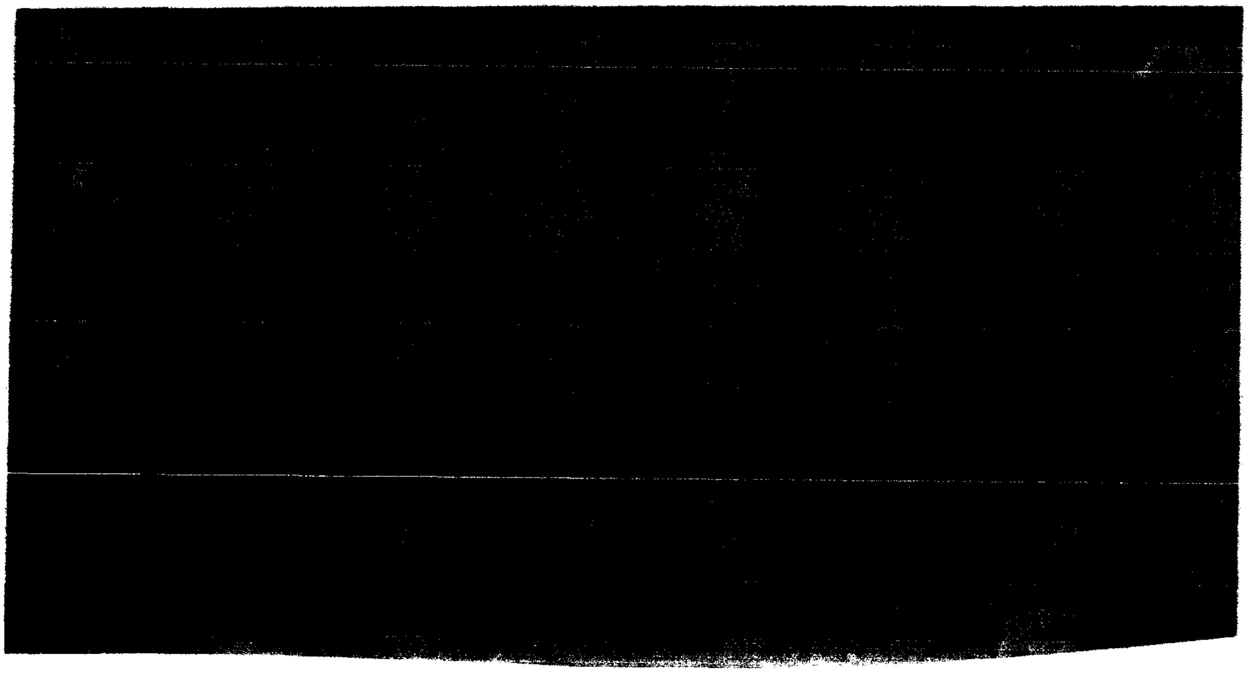

Fig. 1. Geometry for scattering and radiometer measurements.

In terms of this parameter, the conventional radar backscattering cross-section is just $\sigma_{jk}(i,i)$ (incident and scattering angles identical). Also the surface albedo is just

$$\sec\,\theta_o (AI_o)^{-1} \int R^2 I_s \, d\Omega_s$$

which equals

$$(\sec\,\theta_o/4\pi) \int [\,\sigma_{jj}(i,s) + \sigma_{jk}(o,s)\,] \;\; d\Omega_s.$$

A knowledge of the albedo, and the intensity of the thermal radiation falling on the surface, then permits the apparent temperature (the "radiation" temperature) of the surface to be computed in terms of the $\sigma_{jk}(i,s)$. For example, if the thermal radiation is due to a uniform atmosphere of temperature T_{air}, which has a one way transmission factor of $e^{-\alpha}$ at zenith, then the apparent temperature of the surface, for radiation of polarization state j, when viewed from angle θ_i, ϕ_i is

$$(2) \quad T_j(\theta_i) = T_s[1 - (4\pi \cos\theta_o)^{-1} \int [\sigma_{jj}(i,s) + \sigma_{jk}(i,s)]\, d\Omega_s]$$

$$+ T_{air}(4\pi \cos\theta_o)^{-1} \int (1 - e^{-\alpha \sec\theta_s})[\sigma_{jj}(i,s) + \sigma_{jk}(i,s)]\, d\Omega_s$$

where T_s is the assumed uniform temperature of the surface. The derivation of this formula, and a more detailed discussion of the origins and limitations of Eqs. (1) and (2) are given in Reference 1. The point to be made here is that both the radar sensor output (which estimates $\sigma_{jk}(i,i)$) and the radiometer sensor output (which estimates $T_j(\theta_i)$) are controlled by the bistatic cross-section.

Because of the fortunate fact that at microwave frequencies the second term of Eq. (2) (the reflected atmospheric radiation) is often small and fairly stable, the apparent temperature of the surface leads to a good estimate of surface albedo. The interpretation of surface character, particularly when there may be little a priori knowledge of the nature of the surface, can be made with considerably more confidence when both albedo and backscatter can be measured. There is one further point to be made. Actual radiometer antennas are characterized by a power pattern $f(\theta_a, \phi_a)$. Thus the measured (instrumental) antenna temperature T_{ant} of a surface is actually a weighted average

$$(3) \quad T_{ant}(\theta_i) = \int T_j(a)\; f(a)\; d\Omega_a$$

where here the variable (a) refers to the antenna pattern coordinate angles (see Fig. 1b).

To estimate the desired surface radiation temperature, $T_j(\theta_i)$, this equation must be inverted. (The procedure corresponds to a slit-width correction in spectroscopy; it is almost always carried out for radio astronomy observations, but seldom for observations with terrestrial radiometers. The simplest technique is the "bootstrap" method, in which the integral

$$T_{trial} = \int T_{ant}\; f(i)\; d\Omega_i$$

is evaluated, and used to make a first approximation $T_j(i) \simeq T_{ant} - (T_{trial} - T_{ant})$ to the unknown $T_j(i)$; the process is repeated until the estimates converge.)

It is suggested here that (although a series of observations made with a given antenna can be compared without being inverted) meaningful comparisons between the results of different investigators can not be made on the basis of the "raw" antenna temperatures. An example of the order of magnitude of the correction for a good radiometer antenna (first visible sidelobe at -30 dB, back lobes <-55 dB) is shown in Fig. 2 in which the inverted (labelled "radiation") and measured raw (labelled "antenna") temperatures of a smooth asphalt surface are plotted against grazing angle for both vertical and horizontal polarization. A third curve (labelled "computed") shows the theoretical[1] apparent temperature of a smooth surface of the same

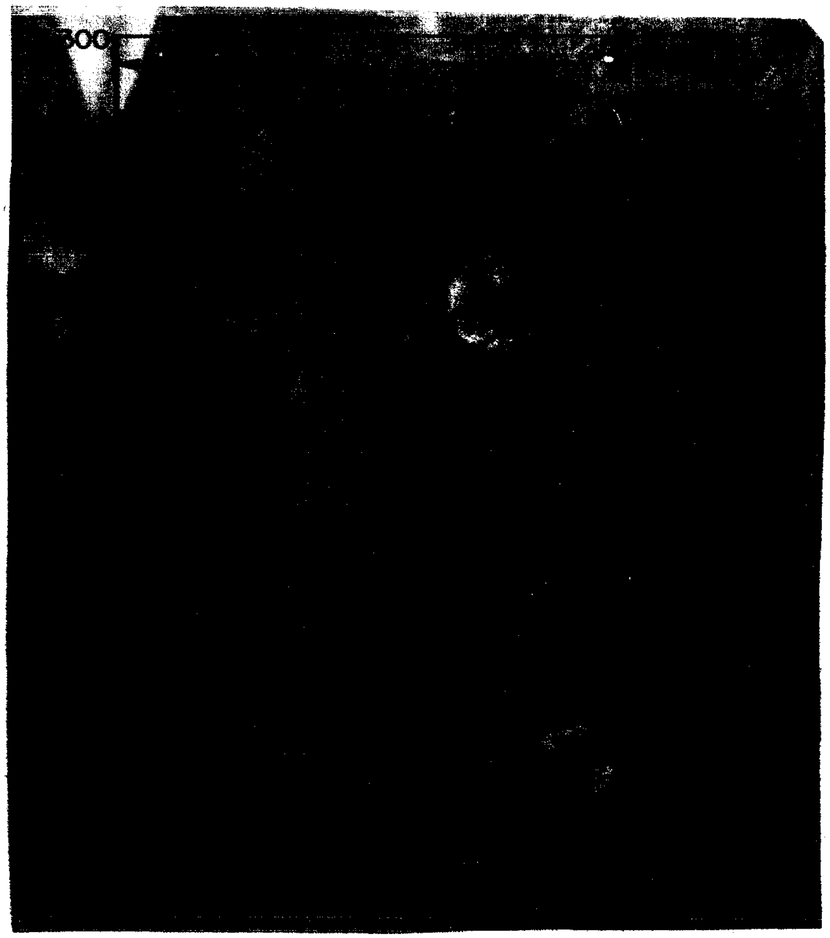

Fig. 2. Measured and computed apparent temperature of an asphalt surface.

dielectric constant. Clearly the antenna pattern correction is a significant one, particularly at the present stage of instrument development, where the precision in measuring T_{ant} is typically less than 1°K. Thus it is suggested that investigators attempting to make quantitative interpretations of surface radiation temperatures always use an estimated radiation temperature rather than the raw antenna temperature.*

III. EXAMPLES OF INTERPRETATION

We wish to give three examples of the kind of information which may be inferred from remote sensor outputs at microwave frequencies. The first is a set of measurements made at the Mono Craters, California on a sequence of lavas of essentially the same chemical composition but different physical properties, ranging from a very light pumice to obsidian. In Fig. 3, the radar backscattering parameter $\gamma_{jk}(\theta) = \sigma_{jk}(i, i)/\cos\theta_i$ is shown as a function of incidence angle for two characteristic forms (measured in situ), at 3 different frequencies. The first form consisted of pea sized pieces of pumice (lapilli) covering a level area of many acres at the foot of one of the cones; the second form consisted of large blocks of low density pumice (0.5 meter to 1 meter). The radar parameter γ for the lapilli surface decreases with frequency, and also decreases rapidly near grazing angles; that is, its return is characteristic of a slightly rough surface.[1] From the fact that the 10 GHz and 35 GHz returns are fairly similar, one may conclude that the transition to a diffuse scattering behavior has occurred by the time the wavelength is 1 or 2 cm, which would imply a surface roughness approximately one quarter wavelength, or 0.25 to 0.5 cm. This is in qualitative agreement, of course, with the known size of the lapilli. The large blocks of pumice, on the other hand (see Fig. 3), exhibit a return parameter almost independent of wavelength, and behave more or less like a Lambert Law surface ($\gamma(\theta_i) \propto \cos\theta_i$; $\sigma_{jk}(i, s) + \sigma_{jj}(i, s) = \gamma_o \cos\theta_i \cos\theta_s$ with γ_o a constant).

Since the apparent temperature of a Lambert surface is independent of viewing angle

$$(4) \qquad T_{Lambert}(\theta) = T_{surface}\left(1 - \frac{\gamma_o}{4}\right) + T_{air}\left(\frac{\gamma_o}{4}\right) F_2(e^{-\alpha})$$

$$F_2(\chi) = 1 - \chi - \chi \ln \chi + (\ln \chi)^2 E_i(\ln \chi)$$

*See note on p. 10.

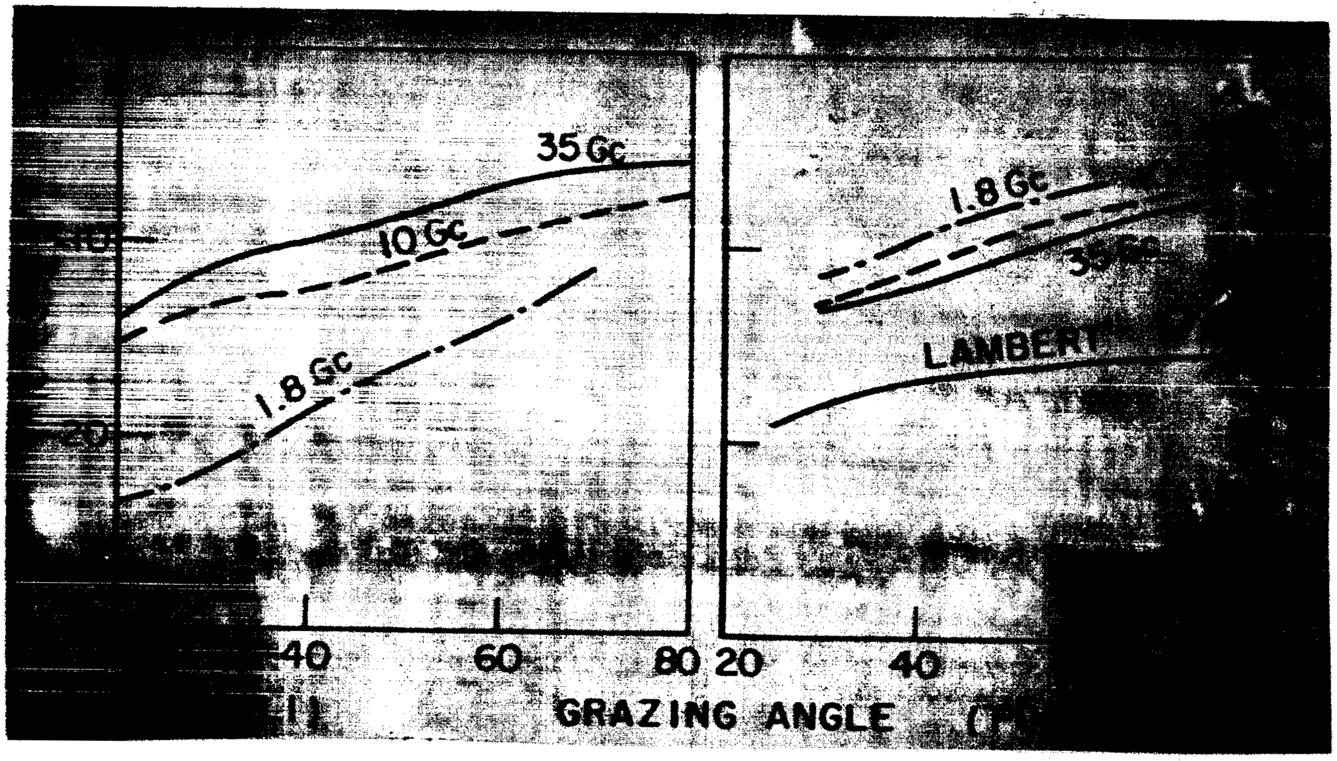

Fig. 3. Radar return from lapilli, and blocks of pumice (density = 0.45). Mono, California.

one would expect the apparent temperature of the large blocks of pumice to be almost independent of θ. That this is the case is clear from Fig. 4 which gives the apparent temperature of three pumices of essentially the same composition (large blocks, ~0.5 meter diameter) but differing in density. The three materials are clearly different in apparent temperature and in emissivity, but since the character of the bistatic scattering coefficient should be the same for all, i.e., approximately Lambert, the differences in temperature must be ascribed to differences in the constant γ_o. This is related to the dielectric constant (values of ϵ for each case are given in Fig. 4) and ϵ, in turn, is related to the density of the material. (An empirical relation between ϵ and ρ suggested by Krotikov,[2] viz, $\sqrt{\epsilon} - 1 \simeq \frac{1}{2}\rho$, is fairly well satisfied by these pumices at 10 GHz.) Thus the microwave radiometer provides a means of distinguishing between pumices of different density, but only when correlated radar observation has established that the angular dependence of the scattering is appropriate to a diffuse scatterer. The apparent temperature of the lapilli, on the other hand

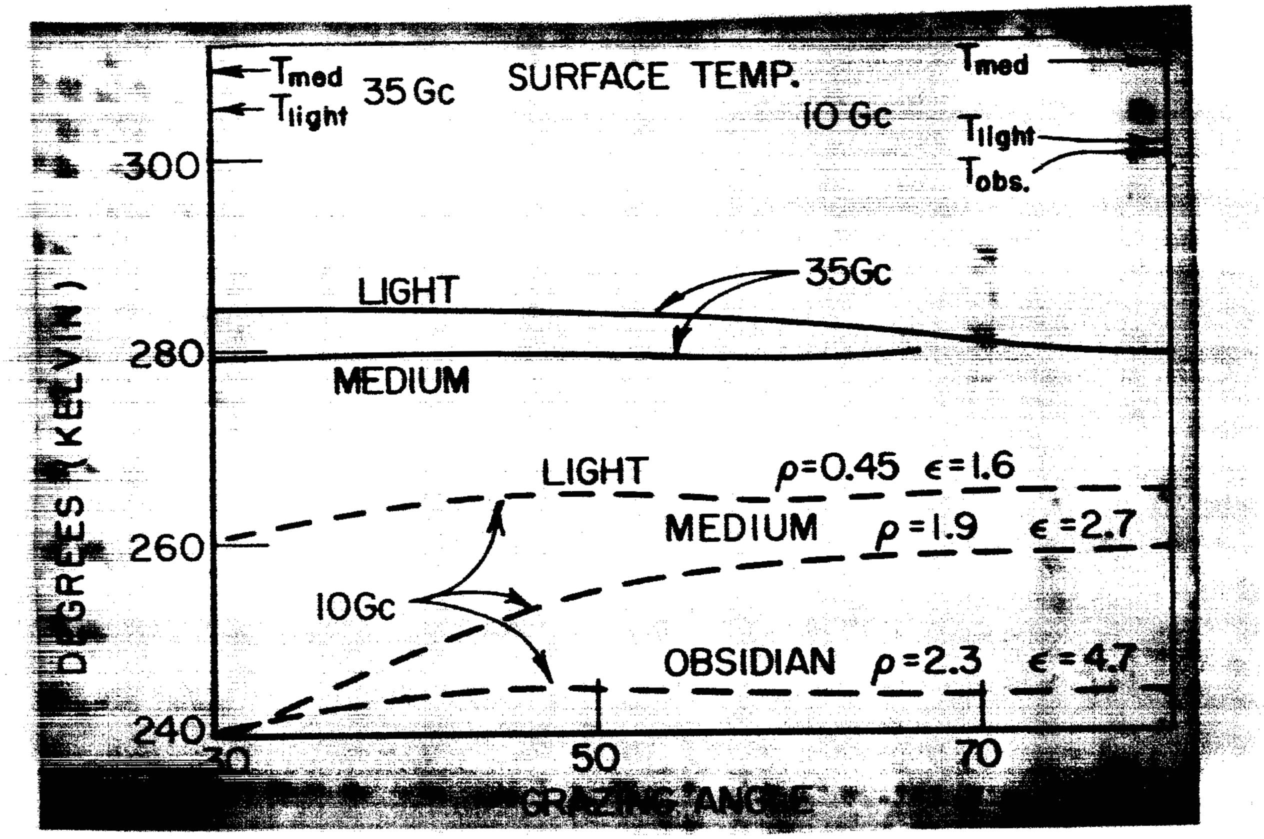

Fig. 4. Apparent temperature of three pumices (Mono, California).

(see Fig. 5) shows a character intermediate between a smooth surface (c. f., Fig. 2) and a diffuse surface (c.f., Fig. 4) (as would be expected from its roughness size), and cannot be interpreted in such a simple way.

The second example of mutual interpretation is provided by a number of crops measured at the Purdue Agronomy Farm, in particular stands of wheat and oats. Here it is more appropriate to consider first the apparent temperatures of the crops (see Fig. 6). These show no evidence of any ground reflection effect (T_v and T_h approximately equal) and have an angular dependence that is in good agreement with temperatures computed from the scattering law $\sigma_{jj}(i, s) + \sigma_{jk}(i, s) = (\gamma_1/2)(\cos \theta_i + \cos \theta_s)$.

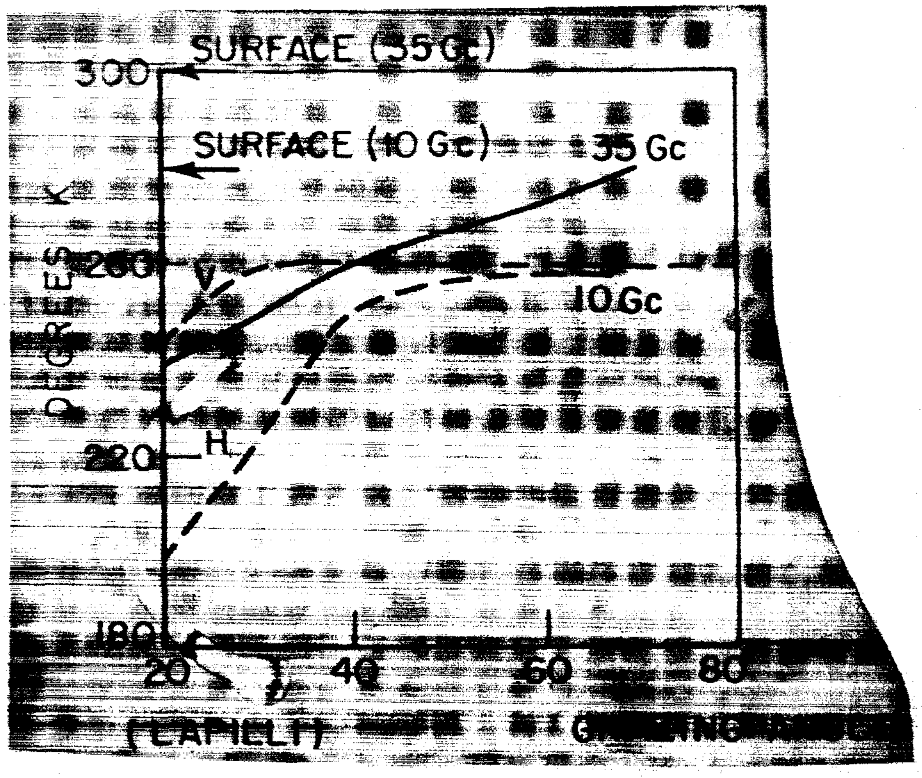

Fig. 5. Apparent temperature of lapilli versus grazing angle (Mono, California).

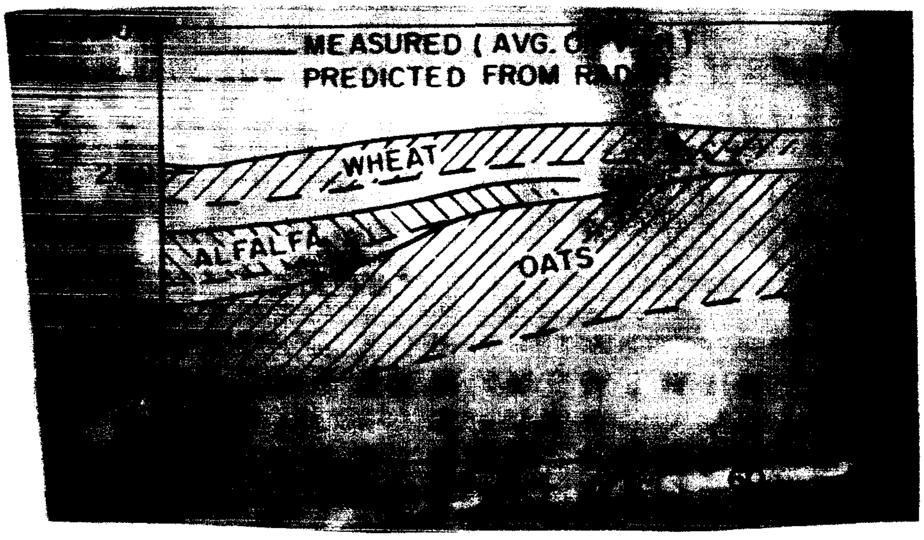

Fig. 6. Apparent temperature at 10 GHz of bulk wheat (60% moisture), oats (76% moisture) and alfalfa (79% moisture) Purdue Agronomy Farm.

$$T(\theta) = T_{surface}\left[(\gamma_1/4) - (\gamma_1/8)\sec\theta\right]$$

$$+ T_{air}\left[(\gamma_1/4)\ F_1(e^{-\alpha}) + (\gamma_1/8)\ \sec\theta\ F_2(e^{-\alpha})\right]$$

$$F_1(X) = 1 - X + \ln(X)\ E_i(\ln X)$$

The temperature $T(\theta)$ predicted from this equation is also given in Fig. 6 (with γ_1 estimated from Fig. 7), and is seen to be in fair agreement with the observed apparent temperatures, correctly predicting the dependence on type of vegetation and on grazing angle. Under these circumstances, the radar return may also be assumed to be due to scattering from the vegetation alone. The point of interest is that oats and wheat have a rather similar structure, yet the radar return from the wheat is nearly an order of magnitude less than from the oats.

At least a part of this difference must be ascribed to the significant difference in moisture content of the two crops. Although there is not as yet sufficient evidence to make quantitative estimates of moisture content from radar return, the above and other[1] evidence leads to the hope that combined sensor outputs in the microwave region may lead to an effective means for estimating crop moisture content.

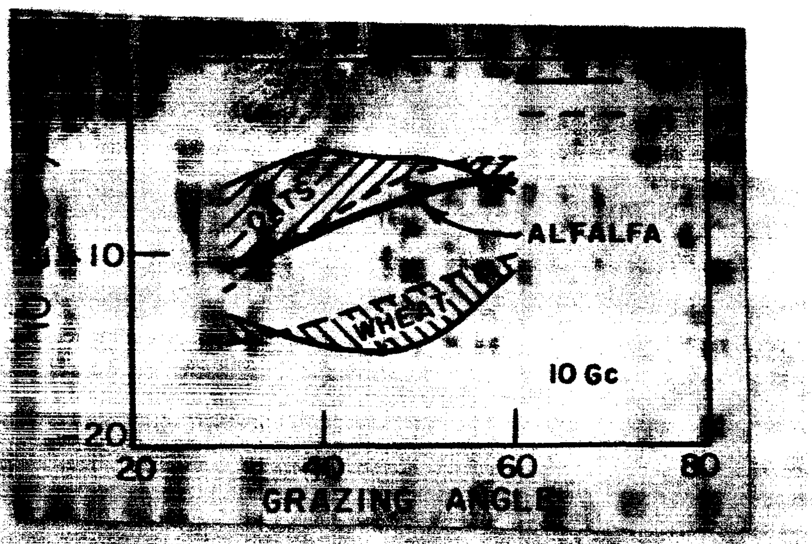

Fig. 7. Radar return at 10 GHz from bulk wheat (60% moisture), oats (76% moisture) and alfalfa (79% moisture) Purdue Agronomy Farm.

A final example may be taken from the asphalt surface of Fig. 2. From the observed temperature profile alone it can be asserted that the small scale structure of the surface is smooth in terms of the wavelength, and has a dielectric constant of about 3, corresponding to the observed Brewster angle of about 30°. (This is slightly lower than the previously known dielectric constant, as measured in waveguide, which would give a Brewster angle of 28°). If now one measures the radar return of this surface (see Fig. 8) and compares it with other smooth surfaces of known roughness one may estimate the mean square roughness at about 10^{-3} cm^2. This is in qualitative agreement with the subsequently measured value of 3×10^{-3} cm^2. Again a combination of sensor outputs has permitted an interpretation which would not be possible from a single sensor alone.

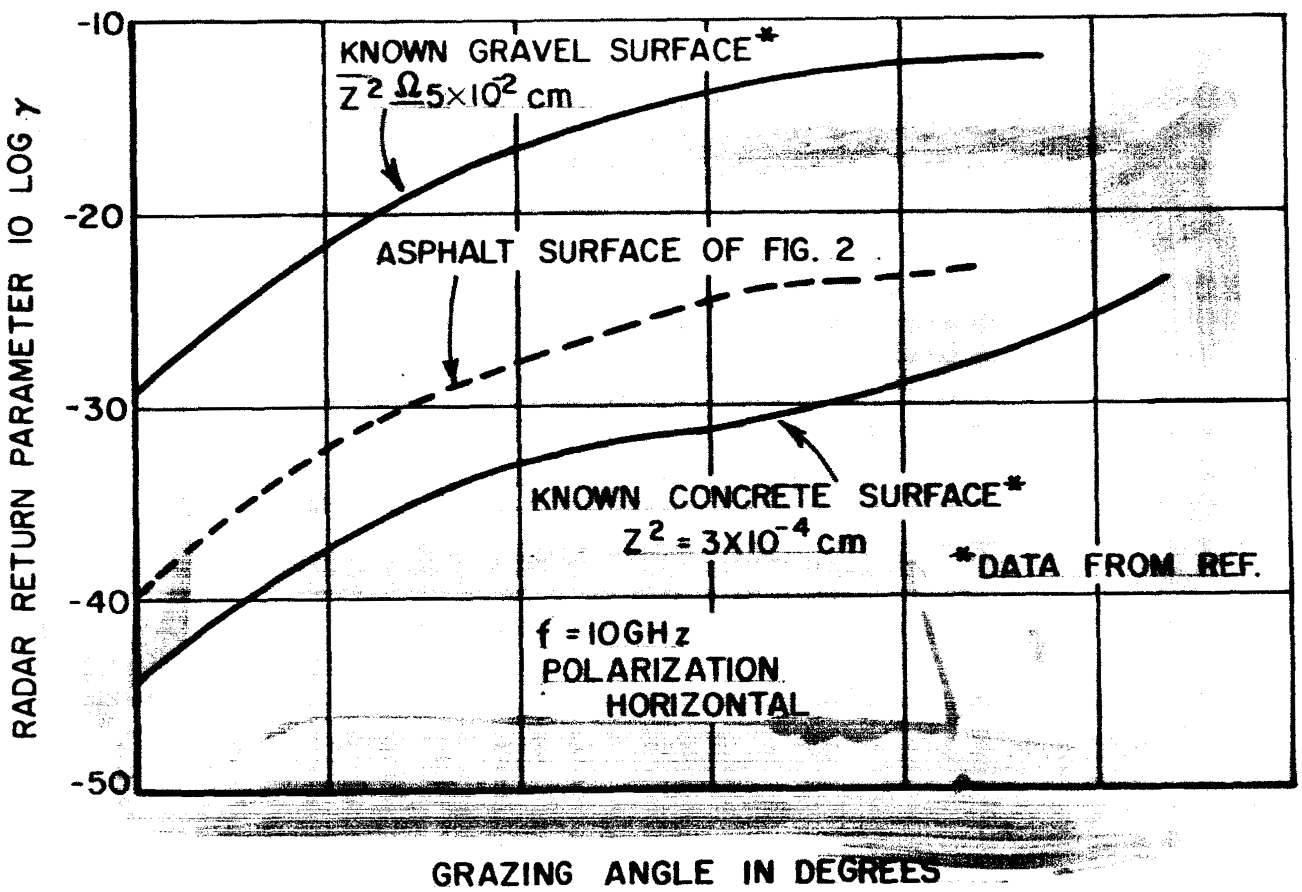

Fig. 8. The radar return from the asphalt surface of Fig. 2, compared with known slightly rough surfaces.

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1. Cosgriff, R. L., Peake, W. H., and Taylor, R. C., "Terrain Scattering Properties for Sensor System Design (Terrain Handbook II)," Bulletin 181, Engineering Experiment Station, The Ohio State University, May 1960.

2. Krotikov, V. D., Izv. VUZ'ov. Radiofisika 5, 1057, 1962.

NOTE

The computed temperature for a nearly smooth surface should be corrected for surface roughness effects. The roughness factor changes the computed temperature by an amount

$$T_{surf}(K\sigma)^2 \left[|R|^2 \delta e^{-\alpha \sec \theta_i} - \int f(i, s) e^{-\alpha \sec \theta_s} d\Omega_s \right]$$

where $\delta = 2 \cos^2 \theta_i$; σ = r.m.s. surface roughness; R = Fresnel coefficient; $f = (\sigma_{jj} + \sigma_{jk})(K^2\sigma^2 4\pi \cos \theta_i)^{-1}$. At the Brewster angle the correction, for vertical polarization, is just

$$\Delta T = -T_{surf}(K\sigma)^2 \int f e^{-\alpha \cos \theta_s} d\Omega_s;$$

i.e., the radiation temperature should be lower than the actual surface temperature by an amount of order $T_{surf}(K\sigma)^2$. This may account for the discrepancy between radiometer and physical temperature observed at the Brewster angle in Fig. 2.

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